Indirect calibration of visible channel data

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ABSTRACT

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To provide quantitative measurements for Earth studies accurate and comprehensive calibration of satellite radiometers is critically needed. The recent increase in the use of satellite data for climate studies calls for the retrieval of physical parameters from the measured radiances and therefore for absolute calibrations that are known over long time periods. However, even the use of classification or "index" type analyses of satellite data to monitor changes in climate requires that the relative stability of the satellite radiometers be known for long-term data sets. Moreover, plans to collect global satellite data over decadal periods, to monitor changes in surface conditions and in climate, require a calibration standard that can be transferred from one satellite to another in a series.

Although most instruments undergo a thorough calibration prior to their launch on a satellite, there appears to be no predictable relationship between these pre-launch calibrations and the post-launch performance. Thus, comprehensive, well-documented post-launch calibrations are needed. Because the solar channels used for imaging on most operational satellites do not have onboard calibration capabilities, a number of indirect approaches have been developed using the Earths surface as a target.

A variety of earth targets have been used in calibration ranging from a single target (such as White Sands, NM) to multiple targets covering the entire globe. The use of such targets to monitor the relative calibration of satellite instruments over long time periods introduces a number of uncertainties such as diurnal and seasonal changes in the radiation from the target as seen by the satellite. These temporal changes arise from variations in viewing and illumination geometry, changes in the atmosphere, navigation errors, changes in the surface characteristics (such as soil moisture and vegetation), and cloud variations. Relative calibration methods require periodic absolute calibration checks. There is a demonstrated need for routine aircraft calibration flights to validate the various approaches.

Introduction

The necessity for accurate and comprehensive calibration of satellite radiometers to provide quantitative measurements for Earth studies is beginning to be realized (e.g., Robinove, 1982; Price, 1987; Slater et al., 1987). The recent increase in the use of satellite data for climate studies calls for the determination of physical parameters from the measured radiances and therefore for absolute calibrations that are known over long time periods. Moreover, plans to collect global satellite data over decadal periods to monitor changes in surface conditions (Price, 1987) and in climate (NASA, 1984) require a calibration standard that can be transferred from one satellite to another in a series. The International Satellite Cloud Climatology Project (ISCCP) has devoted a major effort to the calibration of its data. This effort has paid off in the creation of the first operational, multi-year, multi-satellite, calibrated, visible and infrared radiance dataset.

Although most instruments undergo a thorough calibration prior to their launch on a satellite, there appears to be no predictable relationship between these pre-launch calibrations and the post-launch performance. Thus, comprehensive, well-documented post-launch calibrations are needed. Thermal-infrared channels on most radiometers are calibrated with an on-board thermal source and a view of deep space and are thought to be well calibrated. As the solar channels used for imaging on most operational satellites do not have direct on-board calibration capabilities, indirect calibration using an Earth-target approach is the only method available.

Use of Earth surface targets to monitor the relative calibration of satellite instruments over long time periods introduces a number of factors that are associated with diurnal and seasonal changes in the radiation from the target as seen by the satellite: variations in viewing and illumination geometry, changes in the atmosphere, navigation (Earth-location of the individual image pixels) errors in heterogeneous areas, changes in the surface characteristics (such as soil moisture and vegetation), and cloud variations. An example of the variation of solar illumination is shown in Fig. 1 for three afternoon polar orbiters; the differences in equator crossing time result in significant differences in solar zenith angle. In addition, the effort and expense required to repeat the field measurements many times for many sites usually prevents such programs from being carried out, despite well documented occurrences of significant calibration drifts over the life of some satellite radiometers. Examples are the Coastal Zone Color Scanner (Hovis et al., 1985), LANDSAT 1 MSS (Nelson, 1985), and the NOAA-9 AVHRR Channel 1 (Brest and Rossow, 1991; Staylor, 1990; Whitlock et al., 1990). Figure 2 shows a time history of monthly mean surface reflectance for the Sahara obtained from NOAA-7 and NOAA-9. It illustrates two of the significant calibration problems encountered in collecting a long-term data set. The first is the difference in calibration between satellites, which is responsible for the large increase in reflectance at the satellite changeover. The second is the change in calibration for a given instrument over time as shown by the significant decrease in reflectances calculated using the NOAA-9 prelaunch calibration.

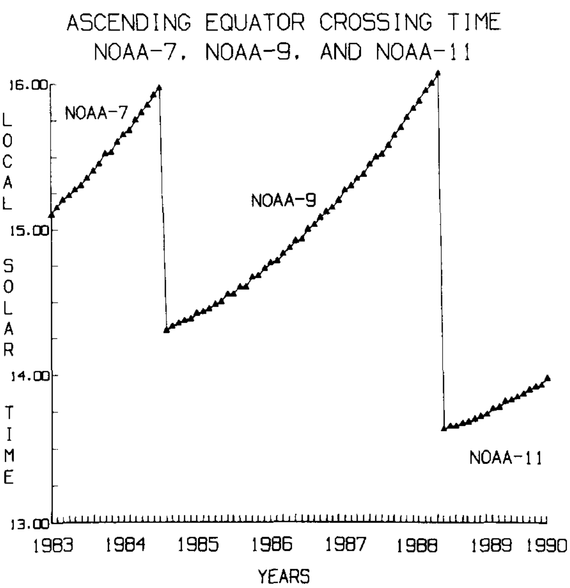

Fig. 1. Time history of ascending equator-crossing times for NOAA-7 and NOAA-9 and NOAA-11.

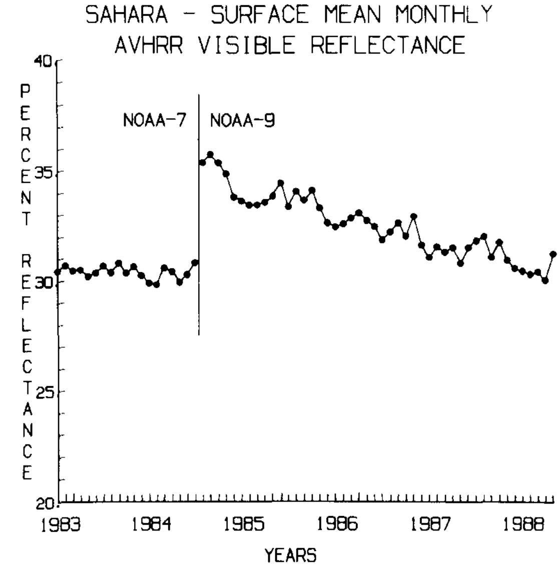

Fig. 2. Time history of monthly-mean surface visible reflectance for Sahara derived from NOAA-7 (pre-Jan 1985) and NOAA-9 (post-Jan 1985) data using prelaunch calibration coefficients.

Discussion

Requirements

Requirements for a viable satellite calibration procedure include a calibration standard that is well-defined and stable over time, a comparison with that calibration standard over most of the dynamic range of the instrument, examination of linearity of instrument response, checks for shifts in spectral response, sufficient temporal resolution, sensitivity studies, and cross comparisons.

Calibration standard that is well-defined and stable over time

When using a natural surface as the calibration standard, this can be a difficult goal to achieve. Even with the use of a single good target, such as White Sands, New Mexico, problems are encountered. Examples are changes in the sand dunes and their shadows caused by the winds (Price, 1987; Slater et al., 1987) and high water tables in some portions that cause variable soil moisture (Frouin and Gautier, 1987; Slater et al., 1987). Desert vegetation can also vary seasonally and from year to year depending on rainfall (Whitlock et al., 1987). The ISCCP calibration program uses multiple targets and is based on the fundamental assumption that the global aggregate of regional variations of surface visible reflectance is not changing with time. Of course, on-going human modifications of the surface and climate are expected to cause some systematic changes in regional surface albedo; however, these changes are not expected to be very large, particularly at 0.6 μm, over periods of 5–10 years (Brest and Rossow, 1991).

Comparison to a standard over most of the dynamic range of instrument

It is critical that the calibration be performed over as much of the range of the instrument's response as possible. For example, calibration at only the low end of the instrument's response then requires extrapolation to the remainder of the instrument's response, and with unknown error (Fraser and Kaufman, 1986). In the ISCCP program, the use of a wide variety of surface types ensures that the measurements cover a large portion of the instrument's dynamic range. The clear sky radiances of some deserts areas are almost 50% of the solar insolation. The use of reflectances (radiance divided by cosine of solar zenith angle) makes the land ice sheets the "brightest" objects, even though their clear radiances are only about 20–30% of the solar constant. This means that any discrepancies in radiance measurements will amplify discrepancies in reflectances for these locations.

Examination of linearity of instrument response

Employment of a single bright target and an assumption about the dark end (space counts) does not allow for assessment of the linearity of the instrument's response. Again, using a large number of targets offers significant advantages.

Check for shifts in spectral response

The recent activity in calibration has focused on response of instruments, and little work has been done on the possibility of spectral shifts from sensor aging (Suits et al., 1988). A method that uses multiple targets, with different spectral response characteristics (e.g., vegetation, snow, sand), could be used to look for such changes.

Sufficient temporal resolution

For an aircraft-based absolute calibration program a reasonable goal would be to aim for four flights per year. This would probably ensure two or three flights and one or two usable calibrations per year. This would not only be a significant improvement over previous calibration activities, but it should be sufficient for a viable calibration program. Whenever there is a change in satellites, the flight schedule should be altered to collect data from both satellites during an overlap period. For a relative procedure, based on the ISCCP experience, two-week data aggregation is sufficient.

Sensitivity studies

This is an important step in the development of a calibration scheme. It is necessary in order to accurately define a threshold at which to act. For example, the ISCCP synthetic sensitivity study (Brest and Rossow, 1991), showed that the method was probably not able to detect a calibration shift smaller than 1–2% (absolute) reliably, especially if the shift was due to a degradation of sensor sensitivity. Therefore, it was initially decided to ignore any indications of calibration change smaller than 2% in the ISCCP results.

Cross comparisons

There are several calibration experiments currently being conducted, each with its own assumptions and limitations, and therefore it is important to compare results. Figure 3 shows a comparison of two different methods. Staylor (1990) has monitored the average of measured visible radiances (converted to narrowband albedo using an empirical bi-directional model for deserts) over the Libyan desert obtained from NOAA-6, NOAA-7, and NOAA-9. The figure shows a comparison of his inferred albedos with ISCCP reflectances for NOAA-9. Despite the different treatments of angle dependence (ISCCP neglect of solar zenith angle dependence in the monitoring procedure causes the small seasonal oscillation in the results), the agreement is excellent: calculated trends are the same to a precision better than 1%. Such comparisons are important to establish confidence in results.

Accuracy

Accuracy requirements can be very severe. Slater (1990) gives some examples of calibration accuracies required in different areas of research. A 10% calibration uncertainty can lead to errors exceeding 50 W m^{-2} in the net shortwave irradiance balance, which is five times greater than the stated goal of an accuracy of ± 10 W m^{-2}. Accuracy requirements for intercalibration with other Earth Observing System (EOS) sensors are: for MODIS, an absolute requirement of $\pm 2\%$; and for MISR, an absolute requirement $\pm 3\%$. Snow surface energy budget models require accuracy $\leq 1\%$. Ocean color (pigment concentration) studies require accuracy $\leq 1\%$.

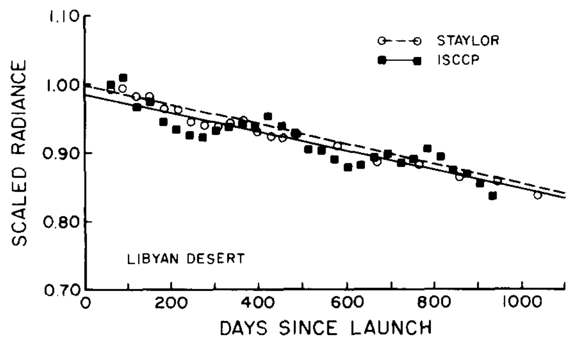

Fig. 3. Comparison of the NOAA-9 sensor degradation as determined by the ISCCP method and by Staylor (1990) using the Libyan desert.

Operational vs. retrospective

Another important consideration is the idea of "operational" vs. "retrospective" calibration. Here operational calibration is taken to mean near real-time calibration that is available to the user almost immediately. Retrospective calibration is defined to be calibrations that are derived by examining trends over months of data; these may not be available until six months or a year later.

Most work to date is of the retrospective calibration type because the operational approach is very difficult to implement. Before implementing an operational calibration program, we must have an accurate knowledge of: the noise inherent in the instrument, the natural variability of the calibration standard, and the limitations of the procedure (e.g., accuracy of radiative transfer codes used). These are necessary in order to choose an accurate threshold to define a calibration change.

Currently our knowledge is limited in too many of these areas to employ an operational calibration confidently. A successful operational approach will depend on the development of long term historical records to characterize the behavior of both the instruments and the calibration targets. Such records are beginning to be developed now. Even when our knowledge of these areas has improved significantly, there will always be a need for retrospective calibration because the operational approach cannot detect slow, long-term drifts. For example the NOAA-9 AVHRR Channel 1 displayed a significant degradation over its lifetime, yet this monotonic decrease was only 0.4% per month, well within noise levels and error estimates of current instruments and methods.

This highlights the need for a multi-level approach: an operational calibration for those users who need it; and a more accurate retrospective calibration (a year or more later) for those who can wait.

Review of current methods

Justus and Slater (in Abel, 1990a) present a comparison of many of the methods that are currently under development. Briefly, they list a number of methods that attempt an absolute calibration using aircraft overflights (Abel et al., 1988; Slater et al., 1987; Guenther et al., 1990), clear sky desert radiances (Slater et al., 1987; Biggar et al., 1990; Teillet et al., 1990; Frouin and Gautier, 1987), or cloud top radiances (Justus 1989); or that attempt a relative calibration using either a variety of global targets (Brest and Rossow, 1991) or deserts (Holben et al., 1990; Staylor, 1990). Each of the methods is categorized with respect to a number of factors, including: cost, frequency, potential for automation, reliance on radiative transfer calculations, number of calibration targets, number of data points, and achievable accuracy.

A cooperative effort is underway to intercompare calibration methods for AVHRR solar channels and to obtain a best value for the absolute calibrations (Whitlock et al., 1990). The comparison of six different sets of measurements provides additional confirmation of the trend inferred for NOAA-9 Channel 1. Trends inferred from the point measurements, which represent independent calibrations at different times, using models, known sites and coincident aircraft measurements, agree well with the two relative satellite methods.

Recommendations

The question remains—which calibration to use? Given the current status of our knowledge, there is general agreement that several independent and redundant methods must be used (at least until some of the unresolved issues are better understood). The best combination of methods would be a relative monitoring procedure tied to periodic aircraft flights. These results can then be compared with one or more of the independent vicarious methods.

Such a procedure has been used for the ISCCP calibration effort. The results of the ISCCP relative calibration, combined with the absolute measurements obtained from simultaneous and coincident aircraft and satellite measurements (from the

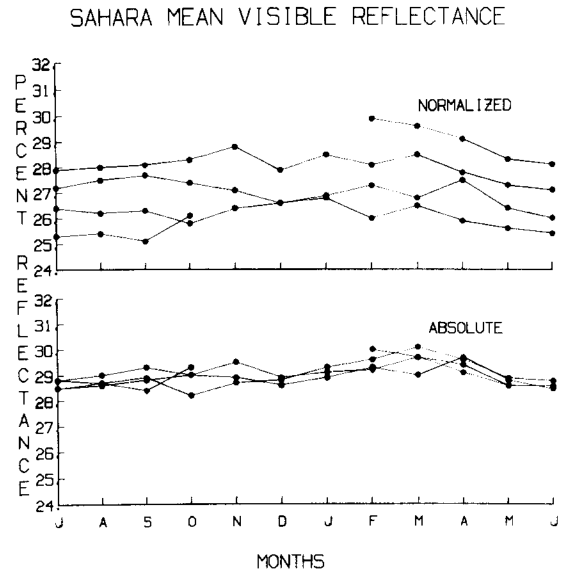

Fig. 4. Time history of monthly-mean surface visible reflectance for Sahara derived from NOAA-9 data. Upper panel (Normalized) is uncorrected data and lower panel (Absolute) is data corrected for instrument degradation.

NASA ER-2 collected in October 1986), provide an absolute calibration for the ISCCP AVHRR Channel 1 data (Whitlock et al., 1990). Having anchored the relative calibration using the October 1986 aircraft observations, the relative calibration trend could be compared with that of another aircraft field program flown in November 1988 (Guenther, 1990). These agree to within 2%. The excellent agreement between the ISCCP calibration and these absolute calibration field programs indicates that the ISCCP calibration accurately characterizes the behavior of the NOAA AVHRR Channel 1 data. Figure 4 shows the results of the degradation correction applied by ISCCP to the NOAA-9 data. Normalized refers to the normalization of the calibration to the ISCCP standard, whereas absolute refers to the correction for the observed instrument degradation. The plot shows the mean monthly reflectances plotted over the course of the year for the almost four years of NOAA-9 data. The top plot shows the degradation of the instrument as each succeeding year of data shows lower values than the previous. In the lower part of the figure, the degradation is corrected and the data points overlap each other. The results of the ISCCP calibration normalization

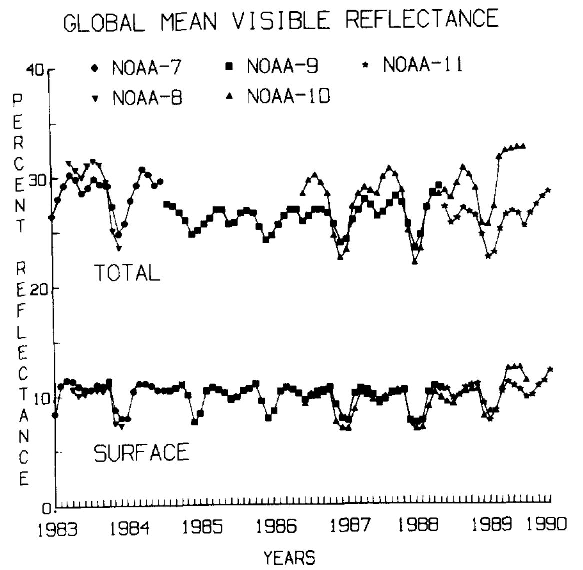

Fig. 5. Time history of monthly-mean global SURFACE (clear sky) and TOTAL (all data) reflectances for all five polar orbiters used in ISCCP to date. Calibration shown includes the inter-satellite normalization and trend-correction steps, but it does not include the final absolute calibration derived from the aircraft-based calibration programs. Calibration for NOAA-10 and NOAA-11 is preliminary.

and trend correction for all polar orbiters since July 1983 are shown in Fig. 5. The figure shows global mean monthly surface (clear sky) and total (all data) reflectance for all five satellites calibrated to the adopted ISCCP standard (note: the final ISCCP absolute calibration derived from the aircraft comparisons is not included in this figure).

Based on what was learned from the calibration program for ISCCP, there are a number of recommendations to be made.

Immediate actions that should be taken are:

—Obtain a consensus on calibration of current (and recent) satellites.

—Provide wide dissemination of results on a frequent basis, either in the form of a newsletter, an online database, or both.

Actions that should be taken in the near future are:

—Formally adopt a particular methodology and set of results as best representing the calibration of particular satellites.

—Make several pre-launch calibrations with the last one being as near to launch as practical. This would provide a better basis for a prelaunch calibration and also might help to avoid the type of problem that arose with NOAA-11 (see Abel, 1990b).

—Plan one month of overlapping data collection operations when a satellite is being replaced by the next in the series.

—Have an aircraft campaign during this time period that calibrates both satellites.

—The data producer should conduct routine statistical monitoring of data as it is being produced. This not only serves as a quality control mechanism, but it can also indicate calibration changes.

Activities that must be begun now, and that will pay off over the long term future are:

—Technological development and implementation of onboard calibration for shortwave channels.

—Develop, test, and implement operational calibration procedures.

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